Design of a Subsurface Moored Acoustic Array in Deep Water

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***Abstract* – The South TOTO Acoustic Measurement Faclility (STAFAC) is currently under development at the Atlantic Undersea Test and Evaluation Center (AUTEC) to become the NAVY's subsurface moored East coast acoustic signature measurement facility. This paper discusses the mechanical design of the subsurface mooring system to support vertical acoustic arrays.**

I. Introduction

The South TOTO Acoustic Measurement Facility (STAFAC) is currently under development at the Atlantic Undersea Test and Evaluation Center (AUTEC) to become the U.S. Navy's East coast subsurface moored acoustic signature measurement facility. STAFAC, with primary requirements of measuring and characterizing the acoustic signatures of subsea moving targets, will replace the surface deployed systems of USNS HAYES with a bottom moored High Gain Measurement System (HGMS) and shore based processing facility. In comparison to other signature measurement facilities where the data processing and analysis are performed in close proximity to the arrays, the challenge for STAFAC is to place the dual array HGMS in a water column 1.35 km (4,442 ft) deep at a remote site 112 km (70 miles) from shore. As shown in Fig. 1, the HGMS arrays will be floated above a subsurface mooring system and must provide the stability required for safe navigation, accurate tracking, sensor orientation, and stability to meet measurement accuracy requirements. Additional requirements include a 15-year service life, a minimum major maintenance interval of at least 5 years, and adequate array recovery and installation procedures for servicing. Relative positioning of the dual arrays, and, thus positioning of the bottom mooring components, in this depth, requires a unique mooring configuration design. The overall approach to designing the STAFAC in-water systems is to use proven products and processes to reduce installation risks, optimize personnel safety, and minimize disturbance of the Bahamas environment. In this paper we discuss the mechanical subsystem design.

II. Overview Of Acoustic Hardware

A. Twisted Bi-Cone Array

The Twisted Bi-Cone Arrays (TBCA) provide specific bandwidth acoustic signature measurements and are mounted in the upper portion of the HGMS cable and are 8 m tall (27 ft) by 2.9 m (9.6 ft) diameter.

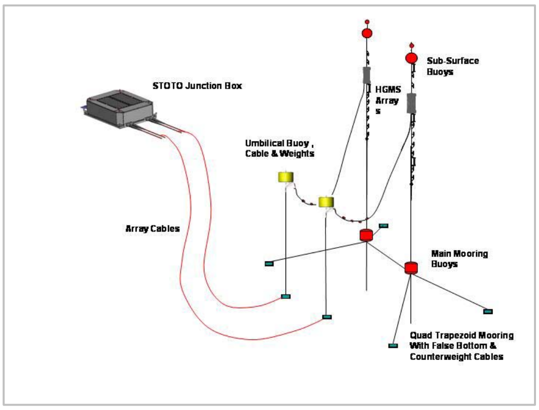

Figure 1 STAFAC Mooring System

The TBCAs are an open frame welded unit made of titanium and contain array hydrophones geometrically positioned on staves as shown in Fig. 2.

B. Vector Sensor Array

For off duty depth measurements, the HGMS legs have Vector Sensor Arrays (VSA) that provide similar array gain to the TBCAs in the same measurement bandwidth. Each VSA contains omni-directional hydrophones and accelerometers which provide focused sound intensity measurements of test vessels. Each is 7.6 m (25 ft) long x 8.9 cm (3.5 in) diameter. The VSAs are located in both upper and lower sections along the HGMS cable and weigh 54 kg (120 lbs) each.

C. High Frequency Array

Two High Frequency Arrays (HFA) are installed on each HGMS leg to provide high frequency measurements at both duty and off depths. The HFAs cover the measurement frequency range above the TBCA and VSA. Each HFA is approximately 2.2 m (7.3 ft) length x 13.7 cm (5.4 in) dia. and weigh 36 kg (80 lbs).

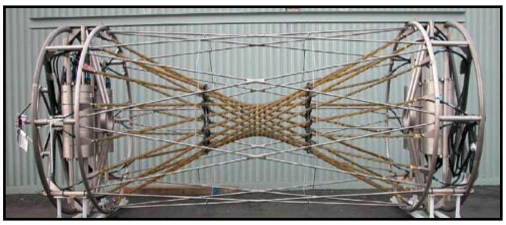

Figure 2 Photo of Twisted Bi-Cone Array

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D. *Wide Band Omnidirectional Hydrophones*

Wide Band Omni-Directional (WBO) hydrophones are installed on the HGMS legs at 30 m (100 ft) increments from nominally 30 m (100 ft) to 236 m (900 ft) to provide broadband measurements of the test vessels. Each WBO is 15 cm (6 in) wide and weighs 1 kg (2.2 lbs).

III. HGMS Performance Requirements

To improve the acoustic measurements, the HGMS arrays must meet specific position and motion performance requirements. A summary of the main requirements are listed as follows:

- Each HGMS array shall be positioned at a minimum of 256 m apart at the center line of the TBCA and shall not become less than 256m and no wider than 274 m apart.
- Each TBCA on the North and South array legs shall be at a specific depth and not displace up or down more than 3m vertically due to ocean currents.
- Each TBCA shall not twist in azimuth more than 1 degree/second due to ocean currents
- Each TBCA shall not be more than 3m depth differential from each other.
- Each TBCA shall not pitch or roll over in tilt more than 2.5 degrees in operational current environments.

IV. Metocean Design Parameters

Ocean currents were measured from an Acoustic Doppler Current Profiler (ADCP) and processed to provide design current profiles. Since the ADCP data was collected between water depths of 30 m (100 ft) to 610 m (2,000 ft) and for certain months of the year, the remaining depths and months required best judgment extrapolation. Ultimately, four operational and survival design profiles were obtained for North, East, South, and West directions. A sample of the ADCP profiles are shown in Fig 3. Temporal changes in the current speed and direction were used for rate of change performance analysis. Surface waves were used in analysis for installation load dynamics from a cable ship as well as for motions of the upper portions of the HGMS array. Random waves with significant wave height of 2.0 m (6.5 ft) and peak period of 7.5 seconds were selected [1].

V. Evolution Of Mooring Designs

During the conceptual design phase, the engineering design team proposed an assortment of concepts for further investigation. The concepts were a culmination of many years design teams past experience with undersea cable structures. Offshore structural analysis software [2] was used to apply ocean currents and surface waves and model the structural response of the array cables and moorings.

A. *Dual Single Point Moorings*

As the simplist mooring configuration, the use of a single point mooring for each of the North and the South array legs, would certainly be the easiest to install and recover while also be the least expensive. A diagram of the dual SPM concept is shown in Fig 4. Mooring analysis checks using the

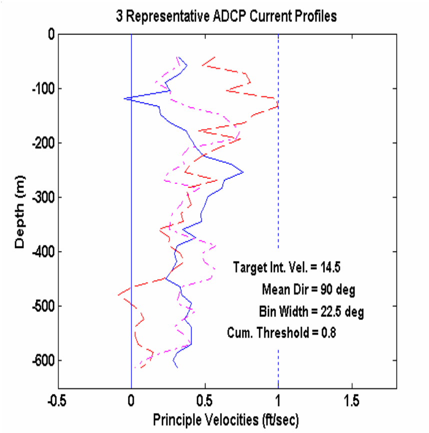

Figure 3 ADCP Ocean Current Profiles

ADCP design current profiles, it became immediately apparent the vertical set-down of the arrays was too excessive in both operational and survival currents. An unacceptable amount of buoyancy and anchoring holding capacity would be required to keep the arrays vertical and would not be practical, nor would the loads be within the working strength of the array cables. Therefore, the dual SPM concept was rejected. Because of the amount of mooring compliance at this water depth, a "False Seafloor Bottom" restriction on the mooring movement would be necessary. In addition, the array is specified to have a 5-year service interval in which the entire array is recovered and either serviced or replaced. With a single point mooring, the anchor and entire mooring would have to be recovered and then reinstalled quite accurately to keep the depth and separation requirements within the specification. This would be extremely time consuming and expensive.

B. *Dual Bi-Mooring Concept*

To create a "false seafloor bottom effect", the Dual Bi-Mooring concept was analyzed. This concept has two mooring legs per HGMS array and is shown in Fig 5. The bi-moor is an attractive concept if the ocean currents were bi-directional a majority of the time or if the operational requirements only had to be met during certain times of the day.

Because of the circulatory rotation of the ocean currents for the test site, the bi-moor concept cannot adequately meet the TBCA set down requirements when currents are out-of-plane direction.

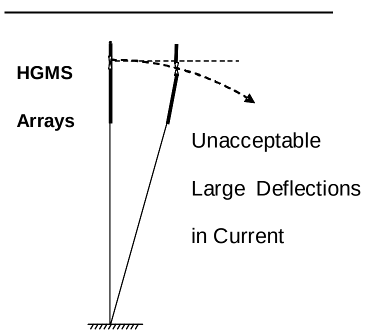

Figure 4 Dual Single Point Moorings

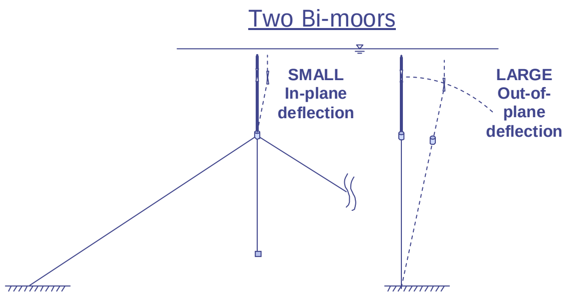

Figure 5 Two Bi-Moorings

C. *Dual Tri-Mooring Concept*

The next logical progression for the mooring configuration was to analyze dual three-point moorings to support the North and South HGMS arrays. The tri-mooring configuration allows constraint for the ocean current direction changes and continues to maintain the “false seafloor bottom effect”. The concept is illustrated in Fig 6. The tri-moor concept was shown capable to meet all the HGMS performance requirements if the anchors could be installed within tight tolerances with an acoustic positioning system. There was a major installation and recovery risk concern for this particular mooring configuration in having mooring legs crossing in the water column due to the water depth and close separation between arrays.

D. Quad Moor Trapezoidal Concept

To maintain the features of the dual tri-mooring concept and alleviate the concerns with the mooring lines overlapping, a quad-moor trapezoid concept was proposed. The quad moor trapezoid combines both tri-moorings with an inner-connect cable and eliminates the third mooring leg from each HGMS array. An interconnect cable takes the place of the third leg from each of the moorings and maintains a certain separation between the arrays. The concept is shown in Fig 7. This configuration became the preferred baseline for further study.

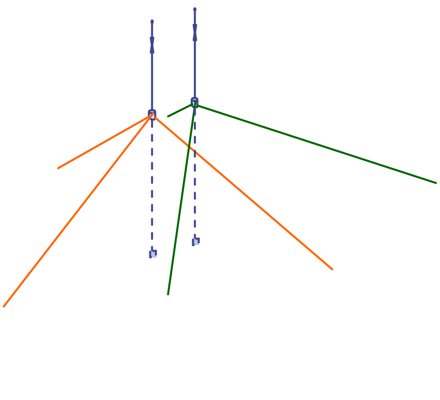

Figure 6 Dual Tri-Moor Concept

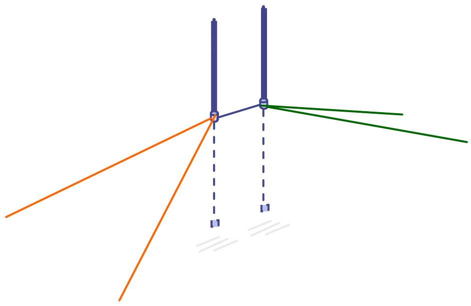

Figure 7 Quad Trapezoidal Moor Concept

V. STAFAC MOORING

A. *Overview*

With the quad trapezoidal concept as a baseline, the complete STAFAC mooring with umbilicals is shown in Fig 8., both in elevation view and plan view. Umbilical cables are attached on the West side of the mooring system to allow cable management on the seafloor and are offset at angles to allow subsea vehicle clearance for navigation. The umbilicals are attached near the upper portion of the HGMS arrays to be consistent with the associate Southeast Alaska Acoustic Measurement Facility mooring system located in Alaska, so that array components could be economically manufactured and readily exchanged for each facility.

The mooring legs are shown with a miminum scope of 1.2 to allow installation and recovery of the main mooring floats and provide lateral and vertical resistance to motions of the HGMS array cable sensors.

During analysis stages, the location of the main mooring anchors, the location of the umbilical anchor, umbilical cable lengths, and amount of floatation were adjusted to best optimize the performance and allow installation and recovery.

The following sections provide details on the mooring mechanical hardware components, primarily the buoys, cables, connectors and anchors with some discussion of installation procedures.

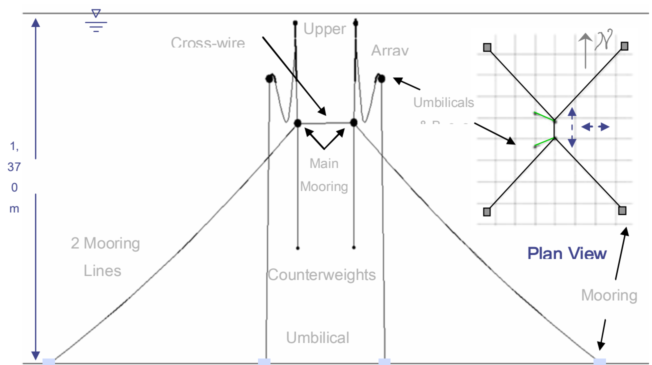

Figure 8 Overview of STAFAC Mooring

B. Main Mooring Subsystem

1. Mooring Cables and Interconnect Cable

There are four mooring legs each 1,646 m (5,400 ft) in length. To prevent failure from fish bite and avoid twisting and hockling during installation, they are made of 5/8” dia. 3x19 Nilspin [3] wire rope which is torque balanced and jacketed. The interconnect cable on the mooring is ¾” diameter Nilspin for support of higher tension loads. Because of the long lengths of mooring lines for the site water depth, initial studies of the mooring included use of synthetic line to save in weight and attempt to reduce amount of required buoyancy. However, because of the deemed high risk of failure from fish bite and subsequent high costs for STAFAC system itself, we decided to use wire rope.

2. Bruce/Clump weight Anchoring System

Because of the water depth, tensions, and mooring line angles it was difficult to find a single anchor that would satisfy all requirements of holding power at such a high angle. Skirted clump weights were considered but abandoned due to stability issues and the difficulty in repositioning them. Drag embedment anchors were considered but eliminated due to high pull angles due to their depth and spacing. Suction piles were also considered but decided not practical. Finally, a combination anchor system was considered which included a clump weight anchor to balance the vertical component of the tension and a drag embedment anchor in series with this to take out the horizontal component of the tension (Fig 9). The clump weight consists of a stack of rail wheels sized for the vertical component and weighing 3,629 kg (8,000 lb) the drag embedment anchor consists of a 1,500 kg (3,307 lb) Bruce FFTS anchor sized for the horizontal component. A half shot of 1-1/2” chain is used between both the bottom end of the Nilspin and the clump weight anchor and the clump weight anchor and the Bruce FFTS anchor. The anchors will be lowered by a crown line connected to the Bruce anchor. This line will also be used as a repositioning line and will be moored to a crown buoy on the surface.

3. Main Mooring Buoys

The mooring buoy is sized to provide an adequate “false seafloor bottom” for the array system. It is located at 427 m (1,400 ft) depth is made from syntactic foam with a steel frame and are 2.1 m (7 ft) diameter x 2.74 m (9 ft) tall, providing 5,440 kg (12,000 lb) buoyancy, shown in Fig 10. Padeyes located on the bottom provide attachment points for the two mooring lines and the cross wire. The center of the buoy is hollow, allowing the counterweight cable to pass through it. Bronze bellmouths are on the

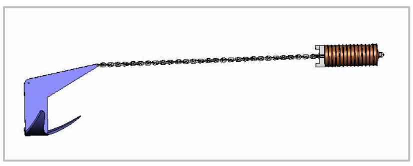

Figure 9 Bruce Anchor with Clump

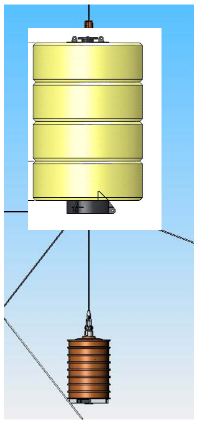

Figure 10 Main Mooring Float System

the top and bottom to prevent cable snagging on the buoy. The top bellmouth also acts as a stop for the stopper which is clamped to the counterweight cable and acts to keep the array at a prescribed depth. It should be noted the counterweight cable idea was originally conceived as part of spinoff of concepts studied in an earlier South TOTO range feasibilty study [4].

C. Array Cable Subsystem

1. Cables

The array system consists of an Upper array, HGMS array, and Lower Array extending from 26 m (85 ft) to 274 m (900 ft) water depth. The Upper and Lower arrays consist of a double armored, torque balanced EOM cable with sensors attached to them. Pressure transducers are located at various locations to determine the depth of the array elements. Between the Upper and Lower arrays is the Twisted Bi-Cone Array (TBCA). It is a relatively fragile assembly and provides the link between the Upper and Lower Arrays as well as the interface point for the Shore Powered Umbilical Cable.

At the bottom of the Lower Array, the counterweight cable is attached. The bottom end of the counterweight cable is attached to the counterweight which is a stack of rail wheels weighing 2,177 kg (4,800 lb). The upper end is attached to the Lower Array. Once the depth of the Mooring buoy is known during installation from acoustic positioning systems, the stopper is attached to control the depth of the array. At the top end of the Upper Array are the Subsurface Buoy and Upper WBO buoy.

2. Cable Connectors

For all of the telecom cable and umbilical cable terminations, we are using Science Applications International Corporation's termination design that consists of a Titanium body, potted strength termination, and redundant Morison type seals for feed through seals. Most of the connectors throughout the assembly are Seacon ® Mini-Con series connectors that also have Titanium shells.

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3. Array Flotation

On each array leg is an upper Subsurface Buoy that is a large syntactic float which provides the main flotation and stiffness for the array. They are each 2.1 m (7 ft) diameter x 2.3 m (7.5 ft) tall and provide 4,536 kg (10,000 lb) net positive buoyancy. Above these floats are small WBO buoys 0.9 m (3 ft) diameter spherical syntactic floats. They provide support for a short length of Nilspin and a couple of additional sensors on one of the arrays. The Upper WBO buoy also acts as an attachment point for the lift/lower line for the array both for installation and servicing and is shallow enough for divers to reach.

B. Umbilical Cable Subsystem

1. Umbilical Cables

The umbilical cable acts as an extension cord between the shore powered array cable on the seafloor and the vertical array system. The umbilical cable is a double armored, torque balanced electro-optical-mechanical cable which is decoupled as much as possible from the array cable to minimize its affect on the array position due to current induced drag forces and cable weight. A large umbilical buoy made from syntactic foam with steel frame supports the majority of the umbilical's length. A catenary shape is employed between the subsurface buoy and the attachment point at the array to minimize the umbilical's impact on the array and to allow the array to be pulled to the surface during servicing and installation without moving the umbilical anchor. A dyna-hanger mechanical system is used for cable connection at the buoy to reduce the moton of the umbilical catenary in changing ocean current directions.

To prevent any obstruction to traveling undersea vehicles, the umbilical cables are oriented 15 degrees in azimuth from East-West headings. They are located on the West side to allow installation and maintenance of the umbilical cables as they head to shore. This asymmetry was inspected under a number of variations to check for slack in lifting of HGMS array cables for servicing with a surface ship and to ensure the HGMS performance requirements were met for all cases. In addition to North and South currents, the East and West currents were used to check the umbilical slack for pulling and pushing the HGMS arrays as shown in Fig 11. and Fig. 12. In East currents, the concern was to not foul the umbilical cable into the WBO hydrophone brackets. For West current, the emphasis was to not tug on the vertical arrays.

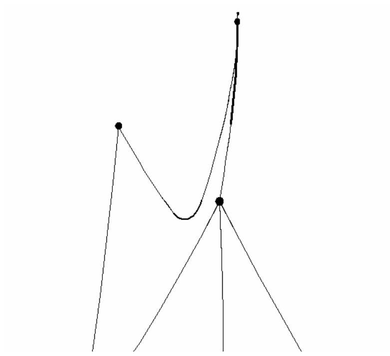

Figure 11 Umbilical Cable in Survival East Currents

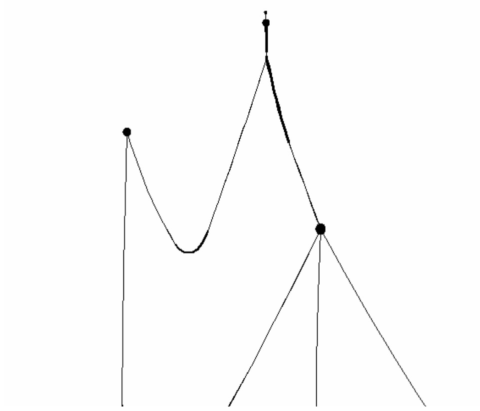

Figure 12 Umbilical Cables in Survival West Currents

The umbilical cables were oriented at azimuth angles offset from due East-West to allow clearance for navigation of underway subsea objects. Studies of 15 and 30 degree umbilical headings were analyzed to check offset of umbilical into navigation pathways for various ocean current headings. Because the umbilicals leading off to the West from the HGMS arrays introduced assymmetry, the racking of the HGMS array had to be checked to maintain performance requirements. The final configuration of the umbilical cables was a design loop check on appropriate slackness for array recovery and installation and tradeoff on pulling the arrays in Westerly current and avoiding fouling of HGMS array sensors in Easterly currents. The addition of in-line umbilical cable weights along part of the cable was required to meet these tradeoffs.

2. Umbilical Anchors

A large clump weight anchor shown in Fig. 13 is made up of a frame with rail wheels weighing 3,629 kg (8,000 lb) that acts as the connection point between the seafloor cable and umbilical cable as well as providing a fixed position on the seafloor for the bottom of the cable.

3. Umbilical Flotation

The umbilical float is a syntactic foam float 2.1 m (7 ft) diameter by 1.5 m (5 ft) tall with 3,629 kg (8,000 lbs) net positive buoyancy as shown in Fig 14. The umbilical cable is routed around the outside of the buoy to allow installation and to provide bending strain relief during recovery operations.

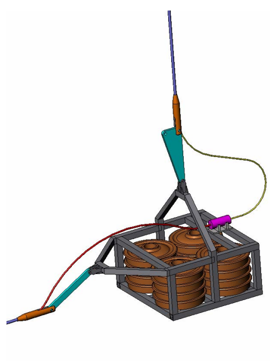

Figure 13 Umbilical Anchor Assembly

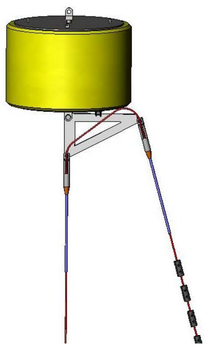

Figure 14 Umbilical Floation

VI. VORTEX INDUCED VIBRATION ANALYSIS

The effects of Vortex Induced Vibration (VIV), alias cable strumming, was checked using VIVA [5] software. In most cases of operational and survival shear currents, only the first and second modes were excited but with minimal amplitudes. The effects of VIV on the HGMS cable was more difficult to estimate due to the abnormal cross sectional shape. It was decided not to add cable strumming suppression to the cables for the mimimal strumming effects.

VII. MOORING INSTALLATION ISSUES

The complete installation sequence of events is beyond the scope of this particular paper, so a portion of the installation is addressed here. During part of installation of the quad trapezoidal mooring legs, the first two moorings on the South side will be installed with anchors in their final resting locations. A crown line will be attached in the event that further movement is needed. The North legs anchors will be temporarily placed closer inwards to allow the main mooring buoys to float at the ocean surface for connection of hardware. The North anchors will be relocated to their final positions thus submerging the main mooring buoys as shown in Fig. 15. A short baseline acoustic positioning system will be relayed from a cable ship to guide a tug boat operator for placement of the anchors to within 30 m (100 ft) position accuracy. The positional accuracy of the anchors is critical to properly position the main mooring buoys such that they are not skewed. Sensitivity studies were conducted using the Orcaflex buoy/mooring software package [2]. Installation Lat/Lon waypoint positions for the ship and buoys will be plotted on navigation charts. Once the anchors are set, the exact depth of the main mooring buoys is not as critical since the counterweight stopper can be set later to correct for the actual installed depth.

The dynamic simulation of re-locating the mooring line anchors showed alternate moorings becoming sufficiently slack to point of laying on the seafloor. The STAFAC site has miminal fouling obstructions, however, subsection flotation may be added to moorings to minimize the laydown effect. Furthermore, simulations provided insight to minimize dragging the moorings along the seafloor.

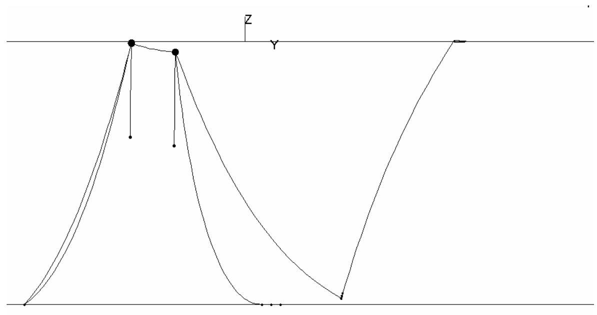

Figure 15 Tug Boat Relocation of North Anchors

VIII. ACOUSTIC POSITIONING SYSTEM

To allow precision installation of the mooring anchors for the main HGMS array and the umbilical anchors, a Kongsberg HiPAP system would be available on the installation vessel. The HiPAP uses both ultra-short baseline system and long-baseline system methods. Specific floatation and anchor locations will be monitored for accurate placement.

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